

Abstract

Title: Fundamental Boiling and RP-1 Freezing Experiments

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This paper describes results from experiments performed to help understand certain aspects of the MC-1 engine prestart thermal conditioning procedure. The procedure was constrained by the fact that the engine must chill long enough to get quality LOX at the LOX pump inlet but must be short enough to prevent freezing of RP-1 in the fuel pump. A chill test of an MC-1 LOX impeller was performed in LN2 to obtain data on film boiling, transition boiling and impeller temperature historys. The transition boiling data was important to the chill time so a subsequent experiment was performed chilling simple steel plates in LOX to obtain similar data for LOX. To address the fuel freezing concern, two experiments were performed. First, fuel was frozen in a tray and its physical characteristics were observed and temperatures of the fuel were measured. The result was physical characteristics as a function of temperature. Second was an attempt to measure the frozen thickness of RP-1 on a cold wall submerged in warm RP-1 and to develop a method for calculating that thickness for other conditions.

FUNDEMENTAL BOILING AND RP-1 FREEZING EXPERIMENTS

Brian Goode

1. LN2 Boiling Heat Transfer Coefficients

The prestart thermal conditioning of the hardware in LOX systems involve heat transfer between LOX and metal where boiling plays a large role. Information is easily found on nucleate boiling, maximum heat flux, minimum heat flux and film boiling for common fluids like water. After looking at these standard correlations it was felt more data was needed for the cool down side transition boiling for the LN2 and LOX. In particular interest is the film boiling values, the temperature at which transition begins and the slope as peak heat flux is approached. The ultimate goal is an array of boiling heat transfer coefficient as a function of surface temperature which can be used in the chilldown model of the feed system, engine and bleed system for X-34.

The first experiment consisted of an actual MC-1 Lox Impeller which had been machined backwards, that was instrumented with 17 surface thermocouples and submerged in liquid nitrogen. The thermocouples were installed on metal thicknesses varying from the thin inducer to the thick hub. Table 1.1 shows the list of tests and impeller orientation. Table 1.2 shows the measurement list.

Table 1.1 Test Matrix

test 1, inducer down orientation
test 2, repeat inducer down orientation
test 3, inducer up orientation
test 4, horizontal 0 degrees up orientation
test 5, horizontal 180 degrees up orientation

Table 1.2 Measurement list

ID	description	thickness
1	exit, hub, 40deg	0.35
2	mid, hub, 40deg	0.70
3	inlet, hub, 40deg	0.35
4	exit, blademid, 5deg	0.07
5	mid, blademid, 35deg	0.07
6	inlet, blademid, 5deg	0.03
7	exit, hub, 220deg	0.35
8	mid, hub, 275deg	0.70
9	inlet, hub, 185deg	0.35
10	exit, blademid, 260deg	0.07
11	mid, blademid, 270deg	0.07
12	inlet, blademid, 260deg	0.03
13	inlet, bladeroot, 170deg	0.05
14	backface, r=1.625, 0deg	0.45
15	backface, r=0.625, 0deg	0.90
16	backface, r=0.625, 180deg	0.90
17	backface, r=1.625, 180deg	0.45

The impeller initial temperature was warm ambient. It was dropped into liquid nitrogen until completely chilled and the 17 transient temperatures were recorded. Figures 1.1 through 1.5 show different views of the impeller and the instrumentation locations. Figure 1.6 shows a chilled impeller in a vertical orientation. Figure 1.7 shows the impeller being submerged in liquid nitrogen in a horizontal orientation.

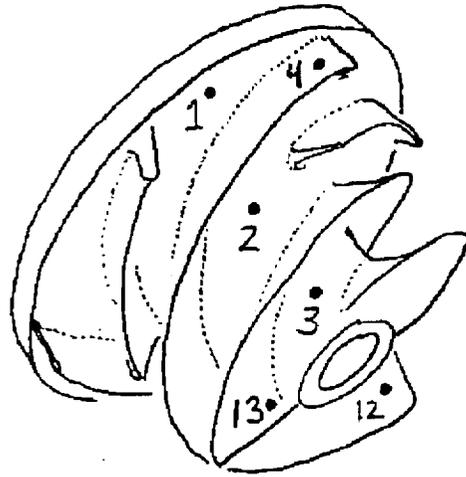


Figure 1.1 Impeller Instrumentation View 1

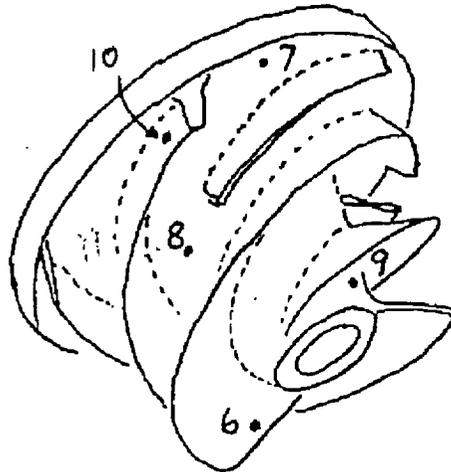


Figure 1.2 Impeller Instrumentation View 2

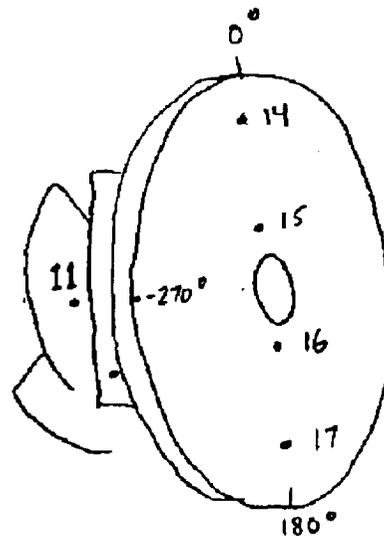
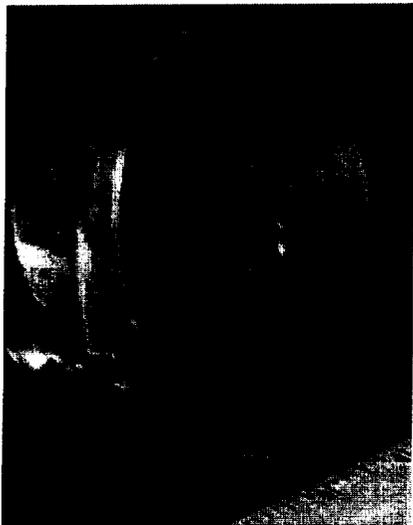


Figure 1.3 Impeller Instrumentation View 3

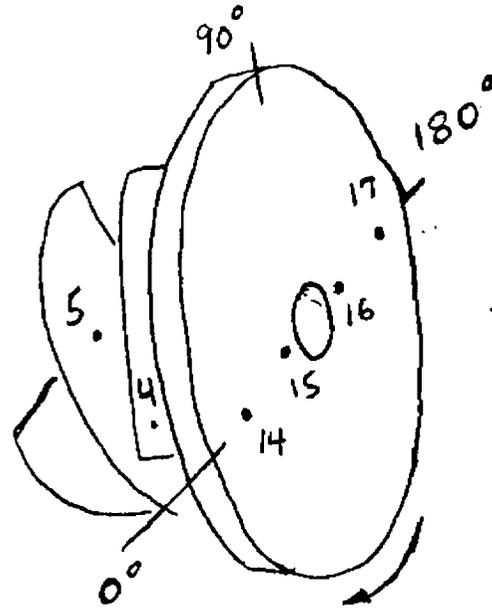


Figure 1.4 Impeller Instrumentation View 4

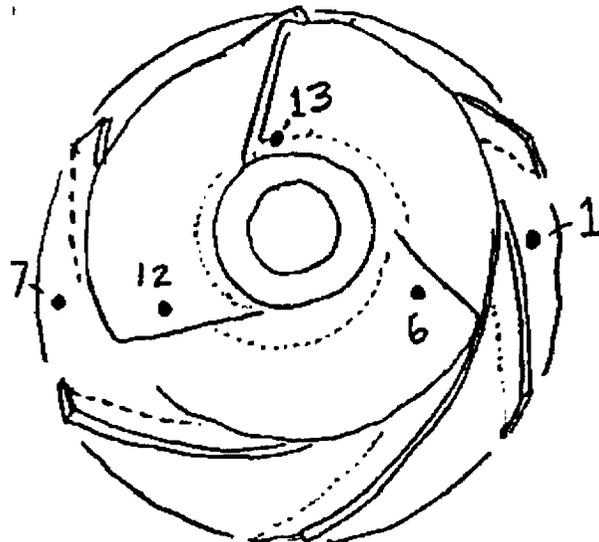
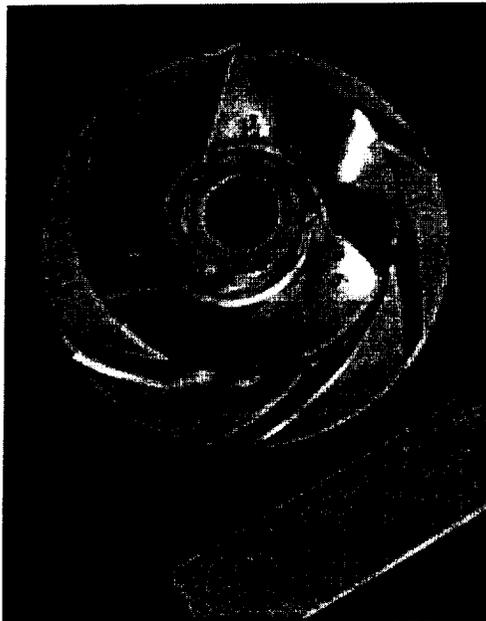


Figure 1.5 Impeller Instrumentation View 5

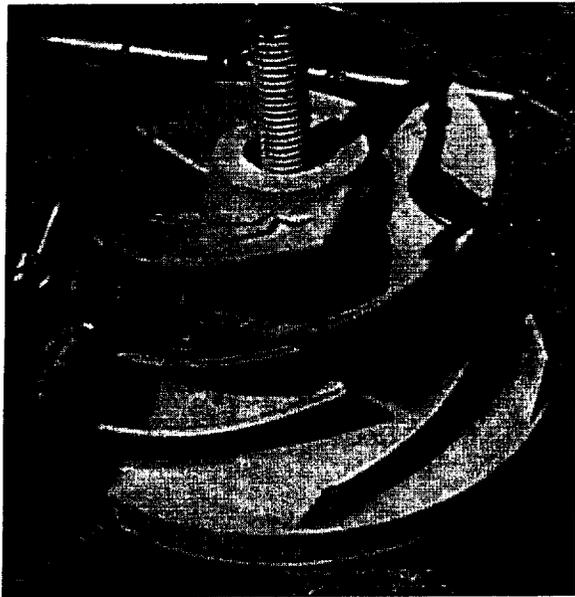


Figure 1.6: Chilled Lox Impeller

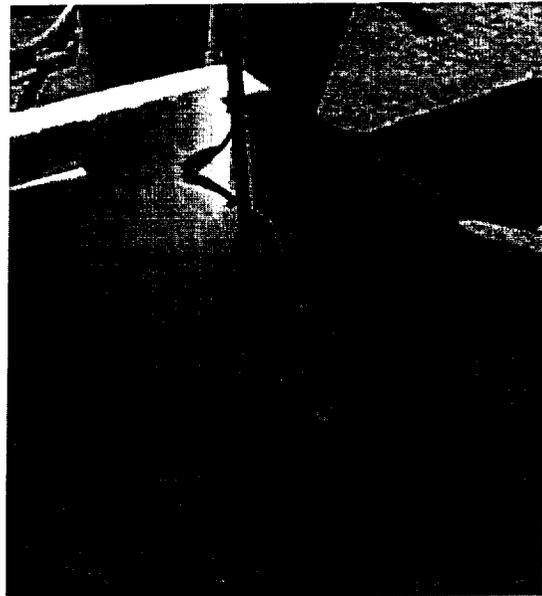


Figure 1.7: Chilling Lox Impeller in LN2

The results of the impeller chill test showed no significant variation with orientation. In general it can be said from this data that when LN2 envelops the impeller, that all surfaces were chilled in 140 seconds. Figure 2.1.8 shows the measured data from an impeller test. Features to notice from the temperature curves are that for thick sections film boiling dominates the chill time until the surface gets to approximately -200 degrees F and then as soon as the transition to nucleate boiling begins to occur the chill time is very short from that point in time

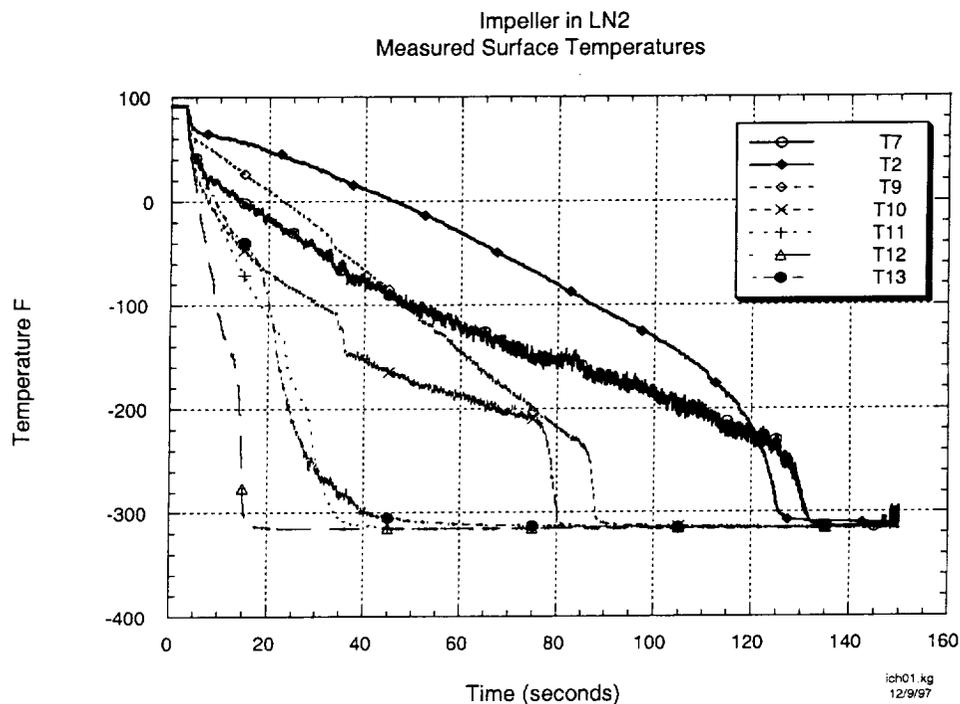


Figure:1.8: Measured Surface Temperatures, LN2 Impeller Test

With this data and a simple thermal model with varying thicknesses, the heat transfer coefficient that is required with time is derived. This is performed for a number of tests and for most of the well behaved thermocouples and averaged to establish a single array of boiling heat transfer coefficient as a function of surface temperature. As a final check this array is used to calculate surface temperature and compared to the measured data. The predictions in figure 1.9 may be compared to measured temperatures in figure 1.8 to see that the array is valid. This approach provided the needed information around the transition temperature that is not readily found in literature.

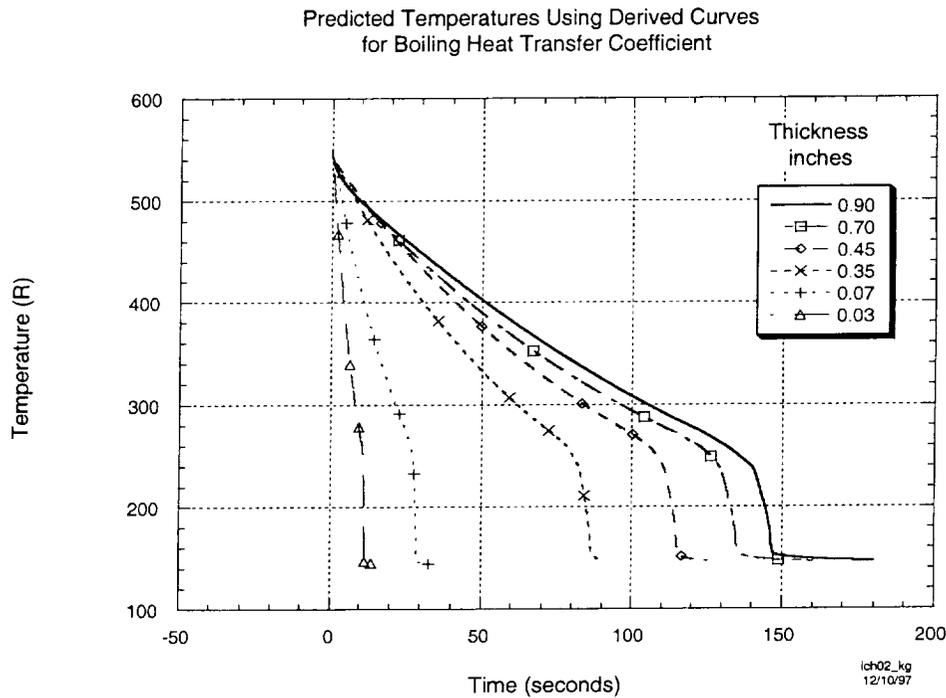


Figure 1.9: Predicted Impeller Surface Temperatures from Derived HTC Curve

2. LOX Boiling Heat Transfer Coefficients

The second experiment measured the surface temperatures of two steel plates chilled in liquid oxygen. The experience from chilling the impeller showed chilldown times sensitive to film boiling and transition boiling heat transfer coefficients and the transition temperature. The LOX testing was performed to get this information for LOX instead of extrapolating LOX from LN2. Figure 2.1 shows the plates in LOX and figure 2.2 shows the instrumented plates on the table. There were two plates 0.25 and 0.1 inches thick made from 304L stainless steel. This testing was performed in open air at a bearing materials and friction test facility operated by Phillip Hall in ED32. The surface temperature was measured and the same approach used from the impeller chill testing to obtain an array of boiling heat transfer coefficient as a function of surface temperature for LOX. Figure 2.3 shows some of the derived heat transfer coefficients before they were averaged. Features to notice on this plot are the two curves with a much lower peak. This occurs with the thin plate where the temperature drops so fast, data recording speed and thermocouple response effects the result. Next time this approach is used, thicker plates would yield better fidelity in the transition and

peak boiling regions. Also notice the bump in the curves at the high temperatures when the plates are first dropped in the LOX. This phenomena was very repeatable and is evidence that it takes a finite time for film boiling to establish. This effect was included in the array for the chill model.

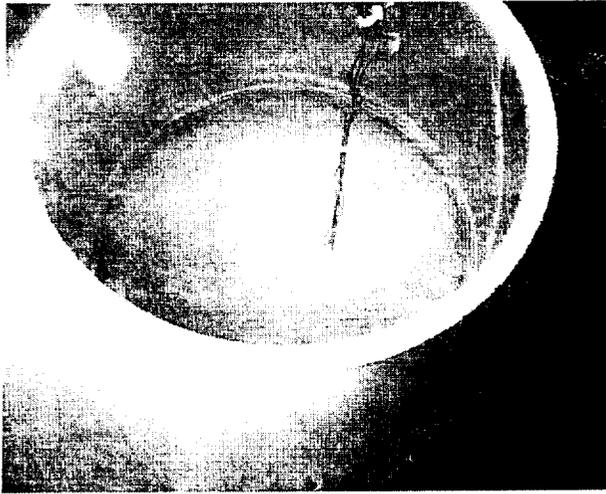


Figure 2.1: Chilling Steel Plates in Lox

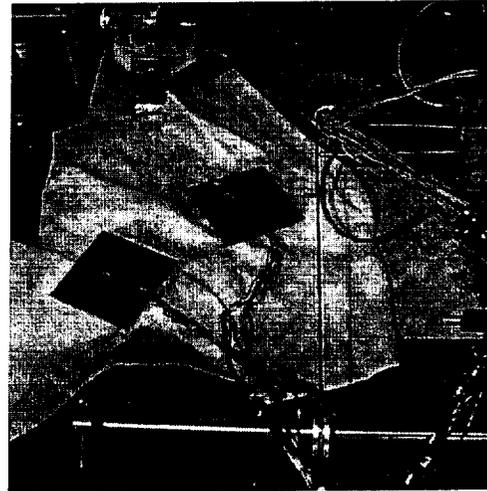


Figure 2.2: Instrumented Steel Plates

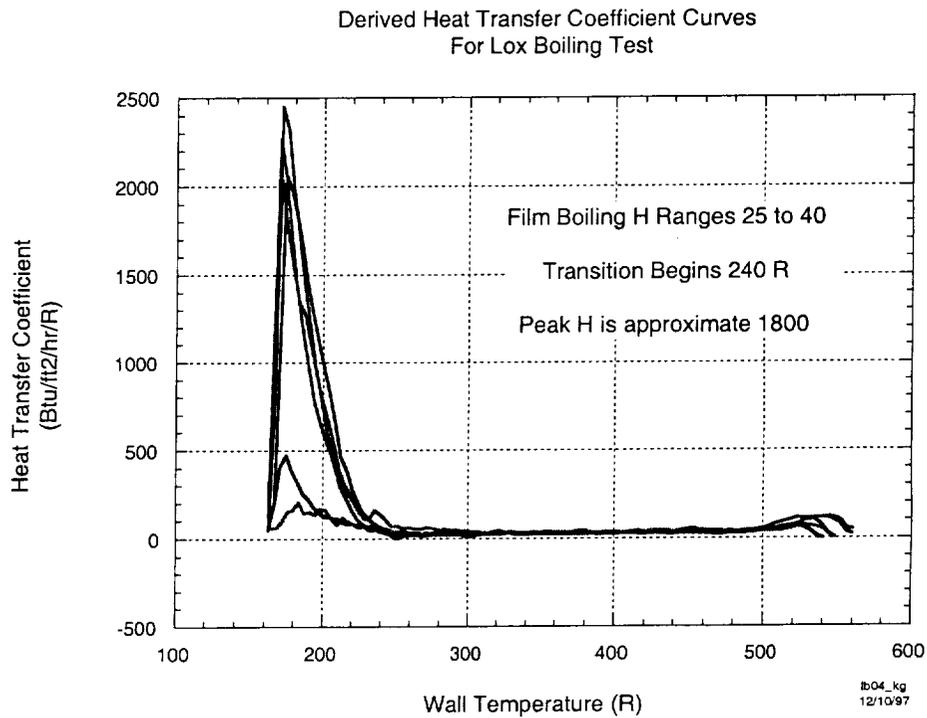


Figure 2.3: Derived HTC Curves from Steel Plates in Lox

The following are the SINDA arrays for boiling heat transfer and low pressures for LOX and LN2. These arrays may be applied for any pool boiling problem using these fluids.

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C
      315 $ H DERIVED FROM STEEL PLATE IN LOX VS. DTE R
C
      where DTE = t wall - t sat(162.3) ,h
      0.,100., 1.7,200., 5.7,1000., 7.7,1800.
      17.7,1500., 27.7,1050., 37.7,665., 47.7,365.
      57.7,154., 67.7,60., 77.7,40., 87.7,19.
      187.7,19., 317.7,26., 337.7,40., 367.7,60.
      377.7,60., 387.7,30., 1000.,30.
END
C
      316 $ H (btu/hr/ft2/r) FROM IMPELLER IN LN2 VS. TEMP DEGR
C
      t wall - t sat(139.2) ,h
      0.,100., 5.8,100., 7.8,600., 9.8,2000.
      14.8,4000., 20.8,3000., 40.8,1000., 60.8,500.
      100.8,120., 120.8,60., 135.8,50., 1000.,50.
END
C

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3. RP-1 Freezing Temperature

To address the concern of RP-1 freezing in a turbopump more information on the freezing temperature was required. At the beginning of the Fastrac program a package was distributed on RP-1 properties from the Chemical Propulsion Information Agency dated 1966. This package in the general identification section lists the freezing point of RP-1 to be -55 deg F (405 deg R). In the military specification section it states that the freezing point must be -40 deg F (420 deg R) or less. A package distributed from Rocketdyne also lists -55 deg F as a typical value. An RP-1 freezing experiment was conceived to determine what the RP-1 freezing limit should be for our application and to observe the characteristics of the frozen fuel to determine at what temperature does RP-1 have the potential to damage hardware or stop flow in the bearing coolant passage.

RP-1 was frozen in an aluminum tray using liquid nitrogen and as the RP-1 thawed the temperature was measured and physical properties were observed. The results indicated that there is no discreet freezing temperature but a transition that occurs between the temperatures of 400 R and 350 R. As temperature is reduced below 350 R the solid wax increases in hardness. These temperatures are approximate because during thaw there were many phases, and temperatures existing simultaneously in the tray. This test showed conclusively that 400 R would be a safe lower limit, and that 335 R represents a significant risk to turbopump operation. RP-1 is shown in figure 1 with a temperature of 373 R (-87 F). Table 1 lists the temperatures and corresponding physical observations.

Table 3.1: Frozen RP-1 Observations

Temperature	Description
302 R	Hard wax
335 R	Solid wax, softening some
350 R	Soft wax
355 R	Gel



380 R Gel, thick liquid, rapid warm up
420 R Liquid RP-1 with some solid present

Figure 3.1: RP-1 at -87 deg F (373 deg R)

Based on the results of this test it was felt that -80 deg F (380 deg R) was a safe condition for fuel temperatures in the bearing coolant passage and the impeller backface cavity. In early testing we picked -60 deg F as a guideline. The operation of the turbopump was not effected in any way when Fuel Seal Drain temperatures were above -60 deg F (400 deg R). All ground test experience was with Fuel Seal Drain temperatures above -60 deg F (400 deg R). A discreet limit for this hazard was never identified however. The following is how the observer guideline was written in the test request for a LOX RP-1 Turbopump.

Observer Guidelines

1. If during the pre-start phase both Fuel Seal Drain Temperatures (E1T1032/1034) are above -65 F no action is required. If one is between -75 and -65 F raise IPS cavity pressure (E3P1028/1029) to 165 psia and proceed. If IPS supply is approximately 165 psia and one FSD temperature is below -75 F do not start the engine. If one temperature is below -65 F, consult MSFC Turbomachinery if available and time permits.

4. RP-1 Frozen Thickness

A second test was performed to determine how much frozen RP-1 would accumulate on a cold wall submerged in warm RP-1. LN2 flowed through the tube, and the wall temperature was measured to be 160 R. Again there was no solid liquid boundary but a transition that occurred as the distance from the wall increased. This made thickness measurements rather subjective. Because of this we had 4 different people measure the thickness and then take an average. The method for measuring the frozen thickness was to use calipers with one side hard against the tube wall and close the calipers until you think you hit frozen RP-1. This distance minus the measured tube diameter is the frozen thickness of RP-1. This test showed that if bulk RP-1 temperatures remained warm no significant buildup of solid RP-1 can take place. Figure 4.2 shows a thickness measurement being taken in this experiment and table 4.1 shows the values for four separate measurements and an average.



Figure 4.2: RP-1 Frozen Thickness

Table 4.1 Steady State Thickness Values

Measurement	Value
A.	.044 inches
B.	.082 inches
C.	.074 inches
D.	.024 inches
average	.056 inches

A conservative approach to calculating frozen thickness was developed using a thermal conductivity of .14 (Btu/ft/hr/degF) and a freezing temperature of -60 deg F (400 deg R). The following is an example using the approach to calculate the thickness on the tube test.

Assumptions

1. The freezing temperature is 400 deg R
2. Warm RP-1 Temperature is 520 deg R
3. The tube OD wall temperature is 160 deg R (Tsat Nitrogen is 144 deg R).
4. RP-1 Fluid properties from CPIA handout at film temperature 460 deg R.
5. Copper tube outer diameter is 0.35 inches

RP-1 Properties

Viscosity $\mu = 27.5 \text{ E-5 lbm/in/sec}$

Thermal conductivity $k = 1.875 \text{ E-6 Btu/in/sec/R}$

Thermal conductivity for solid RP-1 $k = 3.241 \text{ E-6 Btu/in/sec/R}$

Density = sp.grav * rho H2O = $0.83 * 0.03615 \text{ lbm/in}^3 = 0.03 \text{ lbm/in}^3$

Prandtl Number = 65.

Calculate Grashov Number

$$Gr = \frac{g \beta (T_f - T_s) d^3}{(\mu/\rho)^2}$$

$$= \frac{386.4 \text{ (in/sec}^2) (1/460)(1/R) (520-400) (.35)^3 \text{ (in}^3)}{(27.5 \text{ E-5}/0.03)^2 \text{ (in}^4/\text{sec}^2)}$$

$$= 51433$$

Calculate Rayleigh Number

$$\begin{aligned} Ra &= Gr Pr \\ &= 51433 * 65 \\ &= 3,343,145 \end{aligned}$$

Calculate Nusselt Number from Empirical correlation Long Horizontal Cylinder

$$\begin{aligned} Nu &= .48 Ra^{.25} \\ &= .48 (3344500)^{.25} \\ &= 20.5 \end{aligned}$$

Calculate Natural Heat Transfer Coefficient

$$\begin{aligned} H &= k Nu / d \\ &= 1.875 \text{ E-6} * 20.5 / 0.35 \\ &= 1.098 \text{ E-4 Btu/in}^2/\text{sec/R} = 56.9 \text{ Btu/ft}^2/\text{hr/R} \end{aligned}$$

Frozen thickness of RP-1 can be calculated by performing an energy balance at the freezing surface and by knowing that the conductivity of frozen RP-1 is 0.14 Btu/ft²/hr/F (3.241E-6 Btu/in²/sec/R)

$$\begin{aligned} Q/A &= k/x (400 - 160) = h (520 - 400) \\ x &= k(400-160)/h(520-400) \\ &= 3.241\text{E-6 Btu/in}^2/\text{sec/R} * 240 \text{ R} / (1.098\text{E-4 Btu/in}^2/\text{sec/R} * 120) \\ &= 0.059 \text{ inches} \end{aligned}$$

The conclusion that is reached from the investigations into frozen thickness is that as long as the bulk RP-1 is warm, approximately 500 deg R or higher, there should be no concern with RP-1 freezing no matter how cold the hardware is. Also it has been shown that the thickness can be calculated with reasonable accuracy for conditions other than what existed in the test. It is not surprising that we have not noticed any effects of RP-1 Freezing in the either of the injectors even though we predict annulus wall temperatures below the freezing point of RP-1 based on these experiments and calculations.